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A Conceptual Framework for Integrated Stochastic Modeling of Multi-Dependent Systems

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Abstract

This paper introduces an integrated framework and a formal methodology for systematically dealing with multi-way dependencies between infrastructures, and for modeling the combined effects of concurrent failures on all infrastructures in an urban socio-technical system. The research addresses the need to design systems that will be resilient to failures as well as sustainable. Two-way dependencies are not sufficient to model the behavior of such urban systems. Rather, resiliency and sustainability are emergent properties, dependent upon the combined effects of multi-way dependencies between all infrastructures in the system. This was evident in the aftermath of Hurricane Katrina, where several failures were caused not by the loss of a single infrastructure, but by concurrent failures in multiple infrastructures. The objectives are to (1) predict and mitigate the system-wide impacts from spatially and temporally distributed disruptive events that can induce bursts of correlated faults across multiple infrastructures, and (2) to express those impacts in terms that are measurable, quantifiable, and semantically meaningful in a societal context.

1 Introduction

Modern society is critically dependent on complex support systems composed of large numbers of diverse, tightly related infrastructures. Modeling and evaluation of two-way dependencies between isolated pairs of infrastructures has been studied in the past (Mili, et al, 2004). However, two-way dependencies are not sufficient to accurately model the state of an urban system. Rather, resiliency and sustainability are *emergent* properties, dependent upon the *combined* effects of multi-way dependencies between all infrastructures in the system. This was evident in the aftermath of Hurricane Katrina, where several failures were caused not by the loss of a single infrastructure, but by concurrent failures in multiple infrastructures (Mili, Qui, and Phadke, 2004). In order to model, predict, and mitigate the effects of concurrent failures, we present a major paradigm shift to systematically integrate the modeling of complex multi-way interactions between disparate infrastructures. Furthermore, this paradigm moves away from traditional de-contextualized technical analysis by including political, social, and economic dimensions, thereby achieving a holistic approach to socio-technical systems modeling. This approach will create decision support systems to enhance planning, design, and risk management, and to improve the overall situational awareness of emergency management coordinators. This predictive modeling capability will allow emergency management to become proactive rather than reactive, enabling a transformative change in the disaster policy framework.

1.1 Objectives

The primary goal of this research is to develop an integrated, formal methodology for systematically identifying multi-way dependencies between infrastructures, and for modeling the combined effects of concurrent failures on all infrastructures in an urban socio-technical system. The objectives are to predict and mitigate the system-wide impacts of randomly distributed disruptive events that can induce a burst of correlated faults across multiple infrastructures, and to express those impacts in terms that are measurable, quantifiable, and semantically meaningful in a societal context. To achieve these research objectives, we are:

1. Developing formal methods for defining quantifiable, integrated, *system-level* metrics for both resiliency and environmental sustainability.
2. Developing the means to systematically evaluate the impact of sustainability decisions on resiliency and vice versa.
3. Determining how to model complex multi-way interactions between disparate

infrastructures and abstract critical information from diverse, detailed sub-models for integration into a high-level stochastic model.

4. Developing semantics to translate technical state variables into societal dimensions and reason about risk-return trade-offs in a socio-technical context.

2 Background

The Department of Homeland Security (DHS) is the federal agency that coordinates with Emergency Management System (EMS) organizations across the country. DHS has defined 17 critical support infrastructures, focusing on preservation and asset management in the event of a catastrophic event. Although approximately 85% of the infrastructures are owned by private businesses, the EMS is primarily a governmental agency tasked with facilitating disaster prevention and management activities (DHS, 2007) and community decision making (Schneider, 2002). The findings of a recent DHS study indicate the need for the development of robust standardized risk management methodologies, supported by advanced technologies and infrastructures, to maximize the effectiveness of risk management programs (DHS-NADB, 2007). Another key finding supports the importance of risk management leadership that is accompanied by the implementation of a risk management culture and supporting organizational structure to enable the standardization of methods (DHS-NADB, 2007).

Predicting the performance and resiliency of an individual infrastructure generally requires the application of domain specific, high fidelity modeling methods. Each modeling technique has become customized to accurately represent the dynamics and technology of one particular system. Thus, it is not feasible to ask each industry to abandon their individual methods in favor of a single universal modeling method. It is therefore necessary to provide a general framework to integrate a wide array of diverse modeling methods into a single structure.

High fidelity system models tend to be computationally intensive, so that simply merging individual models into a single framework can quickly become computationally intractable. Thus, the modeling framework must extract only the salient features and parameters of each system model at a higher level of abstraction. Such a hierarchical framework for modeling of socio-technical systems would be much more feasible than a flat model.

To date, no such modeling framework exists that is capable of modeling a system as large, complex, and diverse as the infrastructures of an urban environment. This paper presents just such a framework. Used in conjunction with probabilistic risk analysis, it will allow for quantification and predictive modeling to enhance risk management and analysis, thereby to improving the overall decision capability of emergency management coordinators. This would suggest that emergency management would become proactive rather than reactive requiring, a change in the disaster policy framework.

3 Approach and Methodology

Four specific infrastructures are being used to benchmark our theoretical framework in the context of small to large urban cities in the Midwestern United States: *electrical power generation and distribution, transportation, telecommunications*, and *emergency management* (including economic, political, and socio-technical aspects). These four infrastructures are sufficient in number, complexity, and diversity to exercise the methods and demonstrate their scalability and applicability across diverse critical infrastructure components.

The team is collaborating with emergency management coordinators from a set of partner cities, all within a few hours travel time of the Michigan Tech campus. Although the primary emphasis is placed on cities, the roles of county, regional, state, and federal emergency management systems are integral to the overall response to disaster recovery and will also be considered.

The new framework integrates several modeling methodologies of widely varying fidelity, complexity, and level of mathematical abstraction, as illustrated in Figure 1. The three tiers partitioning the vertical dimension represent varying levels of abstraction, while the horizontal dimension represents the spectrum from primarily technical to primarily societal issues.

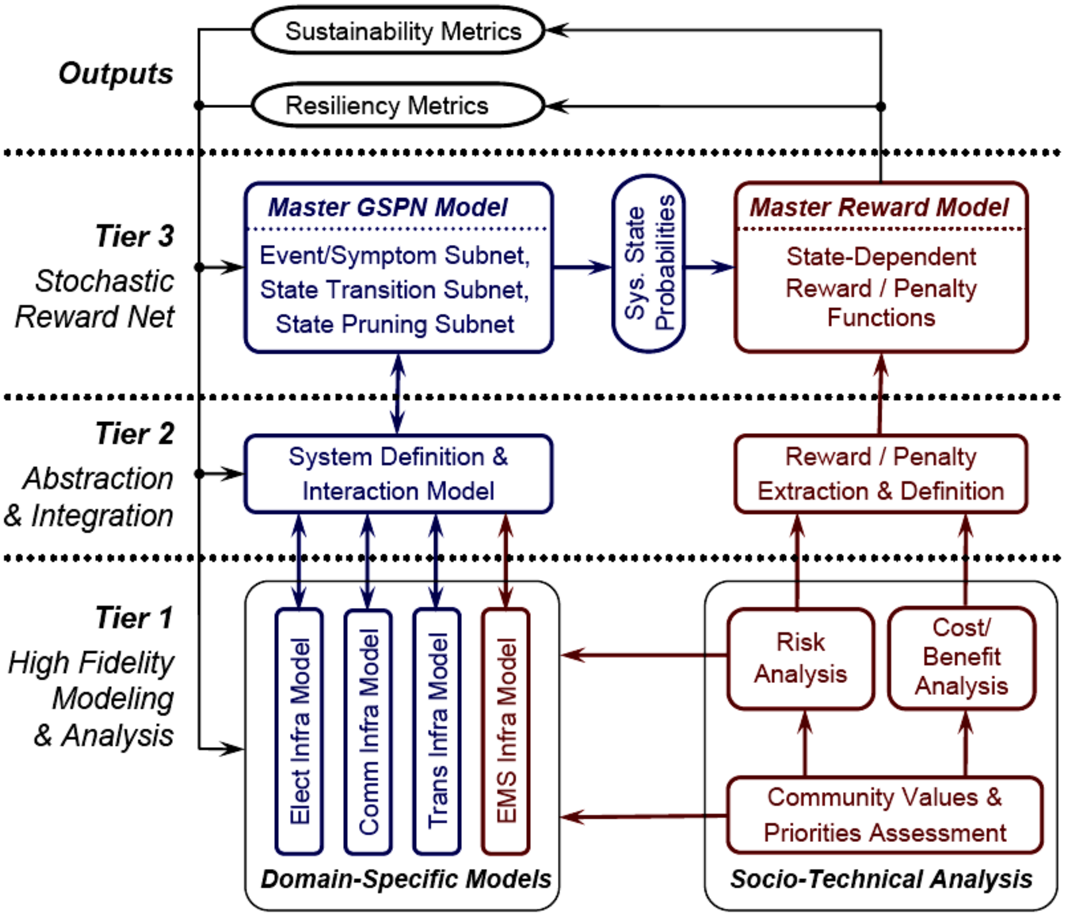

Figure 1: Two Dimensional Modeling Framework

3.1 Tier 1 Components

The lowest level of abstraction in the framework consists of high fidelity, high complexity, domain-specific models and socio-technical analysis methods as described below.

3.1.1 Electrical Power

The electrical infrastructure must be modeled for both generation *adequacy* and system *security*. Generation adequacy refers to the ability of the generation sources connected to the power system to meet the load on the system. For this, a traditional Monte Carlo approach is used, since the availability of a generator as well as the magnitude of the load at any particular time are probabilistic functions (Billington and Allan, 1984). This approach needs to be refined to differentiate between internal causes of generator forced outages and external causes imposed by the interdependencies with the other infrastructures. For example, some of the work done for energy constrained systems (Doorman, et al, 2005) will be followed to represent systems where the fuel has been constrained due to failures in the other infrastructure systems. A similar approach will also be used to include the sustainability aspects of the generation systems.

System security refers to the ability of the power system to survive a contingency, the loss of an element. In this work we will use a probabilistic load flow in order to capture the effect of random events as well as system operation at random loads (Anders, 1990). This approach can also be used to capture "hidden faults" that can lead to cascading failures (Mili, Qui, and Phadke, 2004).

3.1.2 Transportation

We survey methods that have been used to model, and simulate transportation networks specifically with the goal of analyzing traffic flows simulating "what-if" scenarios resulting from catastrophic events. Tools such as TRANSIM (Smith et al., 1995) have been developed to simulate and understand the behavior of transportation networks with respect to traffic flow and have been used in urban planning (Nagel et al., 2000). Cho et al. (2001) developed an integrated operational model that estimates losses due to catastrophic event such as earthquakes on the transportation infrastructures, the industrial capabilities it provides and it economic fallouts. Their research builds on input-output models that can be used to spatially allocate induced economic impacts (Richardson et al., 1993) integrating transportation networks into the analysis.

Perumalla & Beckerman (2006) and Perumalla (2006) have also conducted research on the developing simulations of large scale vehicular traffic networks. The focus of their research has been to use systemic approaches to address computing demands associated with scalability of network size and traffic intensity. Their system, the Scalable Tool for Transportation and Emergency Research (SCATTER) provides us a micro-simulation of traffic within a discrete-event simulation framework. In addition, the system has optimized algorithms and data structures that make it scalable and valuable parallel simulation capability to model large metropolitan infrastructure.

Our framework will be based on the body of knowledge established by these methodologies. We will further the representation and modeling of transportation networks by introducing temporal constraint networks (Anderson, et al., 2007) that will allow us to represent dynamic constraints and information about the traffic networks specifically in relation to other related infrastructure systems. The network will integrate typical traffic patterns, accident rates, information about current pavement condition, last maintenance date and next scheduled maintenance, life cycle costing information of major urban routes (Walls and Smith, 1998), and locations of resources critical to emergency management (Brooke, et al., 2004). We will also employ the *RoadSoft* asset management system to build and maintain this network. Violation of critical constraints encoded within the network will be used to simulate catastrophic failures.

The usage of temporal constraint networks to represent constraints will also allow us to explore different events that can result from different combinations of constraint violations. This will provide us the added advantage to explore all possible unexpected crisis scenarios, specifically the ones that cannot be predicted, because they result from unforeseen combinations of constraint violations. Some such scenarios, though rare, are possible and represent low probability high impact scenarios. This is a significant contribution to analyzing uncertainty and risk from unexpected crisis scenarios in infrastructure systems, compared to traditional "what-if" scenario analysis which tend to analyze outcomes from scenarios that have historically occurred or can be anticipated, not ones that cannot be humanly anticipated, even though they are logically possible.

For example, Cho, et al. (2001) analyzed the impacts of a worst case earthquake on the Elysian Park thrust ramp in the Los Angeles metropolitan area. They selected the scenario based on its potential to cause major damage and casualties. We will use their representational system to analyze the spatial economic impacts of such crisis scenarios. We will analyze low probability-high impact scenarios. In addition, we analyze various other scenarios that have lower impact and higher probability and can cause major inconveniences and system wide impacts on co-related infrastructure systems. For example, as we write this paper (February 26, 2008), Florida is dealing with the consequences of a major power outage resulting from a power station failure. While such an event is not as catastrophic, it can cause major transportation network situations relating to the traffic network flow and safety, among other integrated infrastructural issues.

Finally, our research will provide an integrated approach to analyzing the transportation network in tandem with other co-dependent infrastructure systems. While there has been research conducted in analyzing impacts on the transportation network as well as in simulating inter-modal transportation systems involving freight (Mahmassani, et al., 2008; Beuthe, et al., 2001), there is limited research investigating the impacts of crisis scenarios across multiple codependent infrastructure systems.

3.1.3 Telecommunications

In general, a communication network is considered resilient to a failure if the affected capacities and demand flows can be *rerouted* to paths whose links and nodes have survived the failure mode. The core modeling methodologies for resilient network optimization include Linear Programming (LP) and Mixed Integer Programming (MIP) (Schrijver, 1998). With LP and MIP approaches, a failure state can be specified by vectors of link/node availability coefficients and vectors of demand coefficients. The restoration design/analysis optimization problem can then be modeled as a multi-commodity flow problem constrained by the resilience dimension (Chartrand and Oellermann, 1993).

The resilience design/analysis problem for communications system generally has an extremely large number of variables and constraints. Accordingly, a variety of approximation methods are employed to reduce the number of variables and constraints in exact LP/MIP optimization modeling (Ahuja, et al, 1993; Minoux, 1981; Pidro, 1997; Korst, et al, 1989; Goldberg, 1989), enabling computationally tractable resilience modeling for larger communication networks. To consider sustainability over a long period, a Dynamic Programming Approach can be used to model a resilient communication network evolving over time with varying traffic demands and failure states.

In addition to deterministic (expected) failures and *independent* random failures, the communication system should also be resilient to *correlated* failures caused by a major disruptive event, either directly or indirectly through failures in other interdependent infrastructures. Hence, probabilistic graphic models (Liu and Ji, 2007) and Monte Carlo Methods (Buchsbaum and Mihail, 1995) will be employed in order to derive a set of communication resilience metrics that reflect the impact of communication infrastructures on other interdependent infrastructures, and vice versa.

3.1.4 Emergency Management System (EMS)

As defined by the Department of Homeland Security (DHS) The EMS is the primary governmental agency tasked with facilitating disaster prevention and management activities (DHS, 10/10/07) and community decision making (Schneider, 2002). In addition, DHS findings indicate the need to develop robust *standardized* risk management methodologies, supported by advanced technologies and infrastructures, to maximize the effectiveness of risk management programs (Privacy Impact, 2007). Stochastic modeling of socio-technical systems, in conjunction with probabilistic risk analysis, will allow for quantification and predictive modeling to enhance risk management and analysis, and improve the overall decision capability of emergency management coordinators.

3.1.5 Risk Management Analysis

A critical element of the EMS is risk management. The National Infrastructure Advisory Council, DHS, has defined risk management and identified some specific initiatives. Risk management is defined as “a systematic, analytical process to determine the likelihood that a threat or vulnerability will harm an asset or resource and then identify actions that reduce the risk and mitigate the consequences of the event. (DHS-NADB, 2007)"

Risk to human populations is a function of frequency (occurrence of hazard), severity, and vulnerability. Vulnerability represents a range of factors that express the state of development that determine the amount of damage and loss of human life that a particular hazard can cause (O'Brien and Read, 2005). McEntire (2001) cite a number of factors that are increasing vulnerability and are related to the physical, social, cultural, economic, political, and technical developments of society, tying vulnerability and resiliency together. These dimensions and constructs are key components of complex systems models and are an important input to the domain specific components of the co-dependency model.

Risk assessment and management involve both institutional preparedness and societal attitudes. Risk assessment underpins emergency preparedness and requires a clear understanding of both internal risks and external risks (O'Brien, 2006). Risk is socially constructed and is inseparable from probability and uncertainty (O'Brien, 2006). Risk analysis will emphasize the socio-technical aspects in the consideration of system state probabilities.

3.1.6 Cost/Benefit Analysis

The Committee of Sponsoring Organization (COSO), derived from its findings of the 1987 National Commission on Fraudulent Financial Reporting, developed a framework for analyzing risk assessment to consider qualitative and quantitative objectives that focuses on the interdependencies of an organization's risk tolerance, and allocates response resources based on defined cost and benefit metrics (NCFFR, 1987).

The economic considerations surround the allocation of scarce goods among competing uses and the balance of well intentioned individuals may lead to perceived injustices based on the approach to allot those scarce resources. Economically allocating resources and coordinating the supply of these resources with those who desire them through political process exceedingly difficult (Sobel and Leeson, 2006). Economic allocation requires that both the costs and benefits of activities be considered and politics provides little information about the latter to political decision makers (Sobel and Leeson, 2006).

3.1.7 Community Values & Priorities Assessment

The cultural, social, and organizational dimensions of technical systems, before, during, and after a major disaster, are all essential components to the integration of disparate systems. The degree of miscommunication and intergovernmental unit conflict that arises as a result of such events, can several impact the responsiveness of the emergency management systems team. As an example in during Hurricane Katrina, the role of political and social divide limits the effective mitigation and response causing social vulnerability, housing and sheltering issues, and weakness in other areas (May, 2007).

A unique dynamic involved when elected government officials interact with experienced governmental, nongovernmental, and private organizations to respond in an expeditious manner may be hindered by the miscommunications and sense of urgency of multiple agencies.

The pressure to link disaster recovery to economic development and to deal with the long-term social and economic problems is exacerbated by disasters and presents a paradox (Waugh and Streib, 2006). Because most disaster recovery relies on strong reactive response, even if an organization plans well, it is necessary for emergency managers to innovate, adapt, and improvise because the plans seldom fit circumstances (Waugh and Streib, 2006). This drives the need to identify and understand different states and their probabilities. Not only is system specific technical expertise required but the range of economic, social-psychological, and political resources way heavily on the impact and response to technical system failures. There is a need to foster a sense of community for all the stakeholders involved, including the community, emergency management personnel, public utilities, communication companies, and construction contractors.

Considerations for the community values and priority assessment would include the economic and community decision makers who operate under the premise of full awareness of risk to people, property, economics, societal considerations, as well as environmental sustainability.

Another important dimension is political manipulations in the time of disaster declaration and response. The incentives of political actors are rarely aligned with the interests of society (Sobel and Lesson, 2006). The nature of extreme events leads to the coordination by a governmental agency of private industry and emergent groups that support the relief efforts.

3.2 Tier 2 Components

The middle level of the modeling framework includes a co-dependency abstraction model consisting of system-level parameters defined by inter-infrastructure logical and spatial relationships and constraints. Two classes of algorithms will be implemented at this level. The former will explore combinatorial spaces of constraint violations to identify feasible futures and classify impacts and probabilities of a wide range of scenarios. The latter, rooted in agent based methods (Epstein and Axtell, 1997), will track performance of sustainability and resiliency metrics as emergent properties of the designed complex system.

The first set of algorithms will use a temporal constraint network to represent, integrate and reason about constraint and behavior information from specific domains and the inter-connections between them. A mathematical framework will allow us to represent and reason about domain specific information. The information will include a list of resources, domain activities that they are associated with, relationships between the activities, constraints driving the domain, sustainability variables specific to the domain and the dynamic behavior of each of the variables, and the constraints between the resources in the domain. This framework will be based on a temporal constraint network. Such a network can be developed for each domain and interconnected. The “grand network” representing all the domains and their interconnections can be expressed in first order interval temporal logic semantics. The reasoning will constitute of traversing the network and querying about a very large number of possible futures arising from epistemic events (analytically predictable events that occur due to constraint violations within the domain) as well as alleatory events (random events that are exogenous to the domain, such as an anthropogenic or natural hazard)

The simulation will generate events automatically by querying very large samples of futures, based on all (or appropriately sampled) combinations of constraint violations. In essence, each of these possible futures will be a ``what-if'' scenario that the computer will reason about and automatically generate.  This will protect the system from the biases and shortsightedness of human investigators.  Controlling the scalability and complexity of these algorithms, and ensuring that the ``probabilistic future space'' is exhaustively mined is part of the Tier 3.

The second class of algorithms will analyze the emergent properties of the system. Each of the system properties identified by will be encoded as discrete or continuous variables in the simulation. They will be sampled and queried separately to monitor the ``sustainability health'' of the system. The net sustainability of the system will emerge from the multiple simulated scenarios as the different futures are sampled. The significance of this is that instead of studying specific indicators, or optimizing emissions of specific processes and operations, this method will take a systemic approach and allow us to monitor the "sustainability" of the entire network.

In addition, Tier 2 contains a module to extract quantifiable rewards and penalties from the risk and cost/benefit analyses of Tier 1. While it is extremely difficult to quantify different risk factors in an *absolute* sense, a number of quantification methods, such as Failure Modes and Effects Analysis (FMEA), exist to prioritize risks in a *relative* sense. Methods of this genre will be adapted to prioritize rewards and penalties for resiliency and sustainability.

3.3 Tier 3 Components

The high-level layer of the model must be capable of representing the state of the entire system (city) and computing dynamic state probabilities. Even at a high level of abstraction, the system will most likely present an exceptionally large state space, comprising at least tens of thousands of states. In addition, the high-level model must translate state probabilities into resiliency and sustainability metrics that are meaningful in the social-technical context of the city.

3.3.1 Stochastic Reward Net

A *Stochastic Reward Net* (SRN) (Ciardo, et al., 1993) is a nearly ideal modeling paradigm for the purposes of this project. An SRN comprises a *Generalized Stochastic Petri Net* (GSPN) to evaluate state probabilities, combined with a set of combinatorial *Reward Functions* to compute meaningful rewards or penalties associated with each state of the system (where a penalty is simply a negative valued reward). An SRN has several modeling advantages. GSPNs constitute a powerful, flexible, highly expressive, user-friendly method for representing state-based dynamic systems. As such, they have been applied in a wide range of application domains (Constazltinescu and Trivedi, 1994; Ajmone, et al., 1995; Goddard, et al., 2001; Kieckhafer, et al., 2000; Xue, et al., 1998; Kieckhafer, et al, 1995). It has been shown that a GSPN is isomorphic to a Continuous Time Markov Chain (CTMC); however rather than attempting to visually represent all system *states*, a GSPN focuses on representing only the state *variable*s. Because the number of state variables is generally several orders of magnitude less than the number of states, the GSPN diagram of a system can be dramatically more compact than the CTMC diagram of the same system.

There are several commercial software packages available for solving GSPN models. The general solution approach is to extract the CTMC from the GSPN input file, generate the state transition matrix, and solve the Markov differential equations for individual state probabilities. This project employs a mature and well established program known as the *Stochastic Petri Net Package* (SPNP) (Ciardo, et al., 1989). A major strength of SPNP is that the input syntax is based on the C programming language, allowing all of the functional power of C to be applied to the creation of reward functions for the SRN. In addition, SPNP makes available statistics on each individual state variable or any desired combination of state variables. Thus, the complexity of defining reward and penalty functions is greatly simplified, since the user does not have to identify all states with a particular property of interest.

Some of the traditional constraints on the applicability of GSPNs to general systems have been overcome by recent research results. First, since GSPNs model CTMCs, the distribution functions for state transitions must be exponentially distributed. However, recent results have shown that many non-exponential distributions can be represented by series/parallel combinations of exponential transitions (at the expense of increasing the state space) (Kieckhafer, et al., 2000). Second, dynamic systems can easily generate a huge number of states. Efficient and numerically stable solution of the differential equations then becomes problematic. However, solution engine for SPNP has proven to be extremely efficient, solving as system of

75,000 states in under 5 CPU-minutes on a Sun Solaris server. In addition, user friendly methods have been developed to prune highly improbable, low impact states from the system, in a manner that returns both upper and lower bounds on the results. Thus, trade-offs between of fidelity and complexity can be easily evaluated and adjusted (Mondal, 2002).

The GSPN for this project comprises three subnets. First, an *Event/Symptom Subnet* will evaluate the occurrence probabilities of disruptive events, taking into account such factors as seasonal variations and longer term cycles (e.g. the 1-year, 10-year, and 100-year blizzard). It can also map each event into a set of expected symptoms, to be passed to the mid-layer model, while event probabilities are used internally. Second, a *State Transition Subnet* takes inputs from the event/symptom subnet and the mid-level model and generates state probabilities for all relevant states in the system. Finally, a *State Pruning Subnet* eliminates low impact states from the system, returning both upper and lower bounds on results, so any significant loss in fidelity can be identified and corrected.

3.3.2 Output Metrics

The use of SRN reward functions allows GSPN states to be quantitatively interpreted in a social-technical context. As illustrated at the top of Figure 1, the outputs of the reward functions fall into two classes: resiliency metrics, and sustainability metrics. In this context, “Resilience, as it relates to extreme events can be defined as the capacity of the system, community or society to resist or to change in order that it may obtain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself and the ability to increase its capacity to recover from a disaster (UN/ISDR, 2002, p. 24)." This is determined by the degree to which the social system is capable of organizing itself to increase the capacity for learning from past disasters for better future protection and to improve risk reduction measures (O’Brien, 2006).

Fostering local sustainability in the face of an extreme hazard event, natural or man-made, involves emergency management in the process of community planning and development (Beatley, 1995; Mileti, 1999). It has been suggested that a preeminent objective of emergency management must be to mitigate hazards in a sustainable way and to stop the trend toward increasing catastrophic losses from natural disasters. However, the relevance of emergency management to the task of building sustainable communities is not universally articulated or understood (Schneider, 2002).

Planning for sustainable communities is seen as being directly connected to all community planning, including economic development. It links concerns for social, economic and environmental wellbeing in a coordinated process aimed at meeting present needs (Schneider, 2002). Planning for sustainability is a concept originally associated with environmental policy and now linked to the emergency management function and policy (Beatley, 1995).

Disaster resilient and sustainable communities are product of the building-blocks and tools that create resilience in relation to all economic, social, and environmental concerns (Schneider, 2002) as important inputs into socio-technical analysis.

4 Project Status

At this point in the research, the Tier 1 components illustrated in Figure 1 are the most mature components in the framework. The adaptation of existing, domain-specific modeling techniques is proceeding, with the goal of identifying and extracting those parameters that most impact other infrastructures.

In Tier 2, we need to identify the most robust methods that will allow for integration of the cross-disciplinary systems to allow for succinct data gathering, model building, and analysis of results. There needs to be determination regarding the data requirements, either test or actual data, to be provide the foundation for integration and testability.

At Tier 3, the tools and methodologies for stochastic reward net modeling are well established. Current research is focusing on the interface to Tier 2, and the transfer and abstraction of data across that interface.

5 Conclusions

This research addresses the fact that, pair-wise dependencies between infrastructures are not sufficient to accurately model the state of an urban system. Rather, resiliency and sustainability are *emergent* properties, dependent upon the *combined* effects of multi-way dependencies between all infrastructures in the system. Thus, a new framework has been presented to systematically integrate the modeling of complex multi-way interactions between disparate infrastructures in socio-technical systems that will: (1) hierarchically integrate several modeling methodologies of widely varying levels of fidelity, complexity, and mathematical abstraction, (2) move away from traditional de-contextualized technical analysis by including political, social, and economic dimensions as integral parts of the modeling framework, (3) develop formal methods for defining quantifiable, integrated, *system-level* metrics for both resiliency and environmental sustainability, (4) develop semantics to translate technical state variables into societal dimensions and to reason about risk-return trade-offs in a socio-technical context.

This work addresses DHS concerns about the lack of frameworks that emphasize interdependencies between infrastructures. Specifically, it will: (1) enable the standardization decision support methods for planning, design, and risk management, and improve situational awareness of emergency management coordinators, (2) provide predictive real-time modeling capabilities, allowing emergency management to become proactive rather than reactive, (3) permit the definition of system-wide, quantitative metrics for resiliency and sustainability, enabling quantitative analyses of risk-return trade-offs in a broad socio-technical context.

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